

New prospects for observing and cataloguing exoplanets in well detached binaries

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ABSTRACT

This paper is devoted to study the circumstances favourable to detect circumstellar and circumbinary planets in well detached binary-star-systems using eclipse timing variations (ETVs). We investigated the dynamics of well detached binary star systems with a star separation from 0.5 to 3 AU, to determine the probability of the detection of such variations with ground based telescopes and space telescopes (like former missions CoRoT and Kepler and future space missions Plato, Tess and Cheops). For the chosen star separations both dynamical configurations (circumstellar and circumbinary) may be observable. We performed numerical simulations by using the full three-body problem as dynamical model. The dynamical stability and the ETVs are investigated by computing ETV maps for different masses of the secondary star and the exoplanet (Earth, Neptune and Jupiter size). In addition we changed the planet's and binary's eccentricities. We conclude that many amplitudes of ETVs are large enough to detect exoplanets in binary star systems. As an application, we prepared statistics of the catalogue of exoplanets in binary star systems which we introduce in this article and compared the statistics with our parameter-space which we used for our calculations. In addition to these statistics of the catalogue we enlarged them by the investigation of well detached binary star systems from several catalogues and discussed the possibility of further candidates.

Key words: methods: numerical – catalogues – planets and satellites:detection – (stars): planetary systems – (stars):binaries: general – stars:statistics

1 INTRODUCTION

The first extra solar planet was discovered in the early 1990s by Wolszczan & Frail (1992). Today the statistics of the observations show that the architecture of our solar system seems to be unique compared with exoplanetary systems. At the moment we know about 2000 exoplanets in more than 1200 planetary systems, among them more than 100 exoplanets are in binary-star systems and two dozen are in multiple-star systems. The data of all planets are collected in the Exoplanet-catalogue maintained by J. Schneider¹; whereas the binary and multiple-star systems can be found separately in the catalogue of exoplanets in binary star systems² maintained by R. Schwarz, which we will also introduce in this paper.

Approximately 70 percent of the main- and pre-main-

sequence stars are members of binary or multiple star systems: 67 % for G-M star, e.g. Mayor et al. (2001); and approximately 70 % for O-B stars (e.g. Fabricius et al. (2002), Sana et al. (2012)). Statistics of solar-type dwarfs were studied by Tokovinin (2014) with a distance-limited sample of 4847 targets. A field population was found of about 54% for single stars, 33% binary stars, 8% triple systems, 4% for quadrupole systems, 1% for systems $N > 4$. Observational evidence indicates that many of these systems contain potentially planet-forming circumstellar or circumbinary discs, implying that planet formation may be a common phenomenon in and around binary stars (e.g. Mathieu (1994), Akeson et al. (1998), Rodríguez et al. (1998), Trilling et al. (2007)). This fact led many research groups to examine the planetary formation and evolution and dynamical stability in binary star systems, either in general or for selected systems (Andrade-Ines et al. 2015; Dvorak et al. 2003; Haghighipour 2006; Haghighipour, Dvorak & Pilat-Lohinger 2010; Holman, Touma & Tremaine 1997; Kley & Nelson 2008; Musielak et al. 2005; Paardekooper, Thébault, & Mellema

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¹ <http://exoplanet.eu>

² <http://www.univie.ac.at/adg/schwarz/multiple.html>

2008; Pilat-Lohinger & Dvorak 2002; Pilat-Lohinger, Funk & Dvorak 2003; Raghavan et al. 2006; Saleh & Rasio 2009; Takeda, Kita & Rasio 2008; Thébault, Marzari & Augereau 2010). Despite many theoretical studies on the planetary formation in double star systems, the formation processes are not entirely understood (Kley & Haghighipour 2015; Bromley & Kenyon 2015; Jang-Condell 2015; Gyergovits et al. 2014).

From the dynamical point of view the binary star systems as well as multiple star systems are particularly interesting. According to the work of Rabl & Dvorak (1988) one can distinguish three types of planetary orbits in a binary star system:

- (i) S-Type or circumstellar motion, where the planet orbits one of the two stars;
- (ii) P-Type or circumbinary motion, where the planet orbits the entire binary;
- (iii) T-Type: a planet may orbit close to one of the two equilibrium points L_4 and L_5 ; we call them Trojan planets. The dynamical study of Schwarz, Süli, & Dvorak (2009) could show with a few real binary systems that the T-Type configuration is not only of theoretical interest and Schwarz et al. (2015) could show that T-type orbits can be detected with ETV signals.

The graphic representation of the different dynamical scenarios is given in Fig. 1. The first planet in P-Type motion, was detected in 2009 (HW Vir (AB) c, Lee et al. 2009)³. Since that time planets in well detached binary systems become more and more attractive, especially tight coplanar circumbinary planets around short-period binaries (Hamers 2016). Further P-Type planets were discovered in the following years, where especially the space-mission Kepler was very successful. Among them are also multiplanetary circumbinary systems, like HW Virginis or Kepler 47 (Orosz et al., 2012).

From the observational point of view well detached binary star systems with separations smaller than 3 AU are more interesting than wide binary systems because the observation time for the latter ones is much longer. Furthermore, well detached binaries offer reasonable signal-to-noise ratio (S/N) values for photometry and radial velocity (RV) amplitudes (Guedes et al. 2008; Beaugé, Ferraz-Mello & Michtchenko 2007; Malbet et al. 2012; Eggl, Haghighipour & Pilat-Lohinger 2013).

A first study of test particles in circumbinary orbits was presented by Dvorak (1986), Dvorak et al. (1989) and Holman & Wiegert (1999). Schwarz et al. (2011) studied the dynamics of binary star systems with a circumbinary planet, and calculated its eclipse timing variations (ETVs) for different values of the mass ratio and orbital elements of the binary and the perturbing body.

Most observations of planets in binaries are focused on $\mu \approx 0.5$ (stars have similar masses) and are restricted to Sun-like stars. In Fig. 2 we show a distribution of the mass

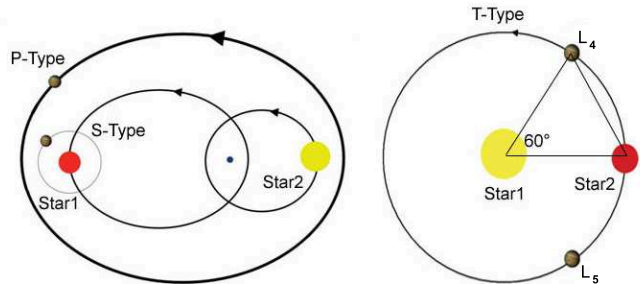


Figure 1. Scheme of the 3 different dynamical possibilities of planets in double stars. A colour version of this figure is available in the online version.

ratios of all detected exoplanets in binaries and we found that the most common mass ratios $\mu = \frac{m_2}{(m_1+m_2)}$ are $\mu = 0.25$ and 0.5 . Therefore we use different mass ratios for our simulations for P- and S-Type systems.

This paper is divided into three parts: the first part is devoted to the possible detection of exoplanets in well detached binary star systems in P- and S-Type motion by the help of eclipse timing variations (ETV). In the second part we prepare statistics for well detached binary star systems from several catalogues and discussed the possibility of further candidates. The actual statistics of planets in binaries and multiple star systems are taken from the catalogue of exoplanets in binary star systems which we introduce in the chapter 6.

2 NUMERICAL SETUP

2.1 Models

The photometric detection of extrasolar planets is of particular interest for the discoveries in eclipsing binaries. We investigated well detached binary star systems, where the initial separation of the stars is 0.5 to 3 AU. From the dynamical point of view these initial separations are very interesting, because planets in S- and P-Type orbits are possible and they are supported by the first Kepler discoveries of a long ($\approx 400^d$) eclipsing binary with a pulsating red giant component (Hekker et al. 2010).

We studied the planar full three-body problem (3BP) with numerical integrators. In this problem two finite bodies, the primaries ($m_1 = \text{primary star}$, $m_2 = \text{secondary star}$) revolve about their common center of mass, starting with three different eccentricities ($e_2 = 0, 0.2, 0.4$). A third body $m_3 = \text{planet}$ moves around m_1 for S-Type or around both stars for P-Type motion in the same plane as m_2 .

We have regarded all the celestial bodies involved as point masses and integrated the equations of motion for a time up to $T_c = 10^3$ yrs for the ETV-maps shown in section 3 and 4 and $T_c = 10^6$ yrs for the stability limits. For our simulations we used a Gauss Radau integrator with an adaptive step size (see Eggl & Dvorak 2010, and references therein) for the ETVs and for the stability the Lie-method with an automatic step size control to solve the equations

³ Newer investigations of (Funk et al. 2011) and (Horner et al. 2012) found that this system is controversial.

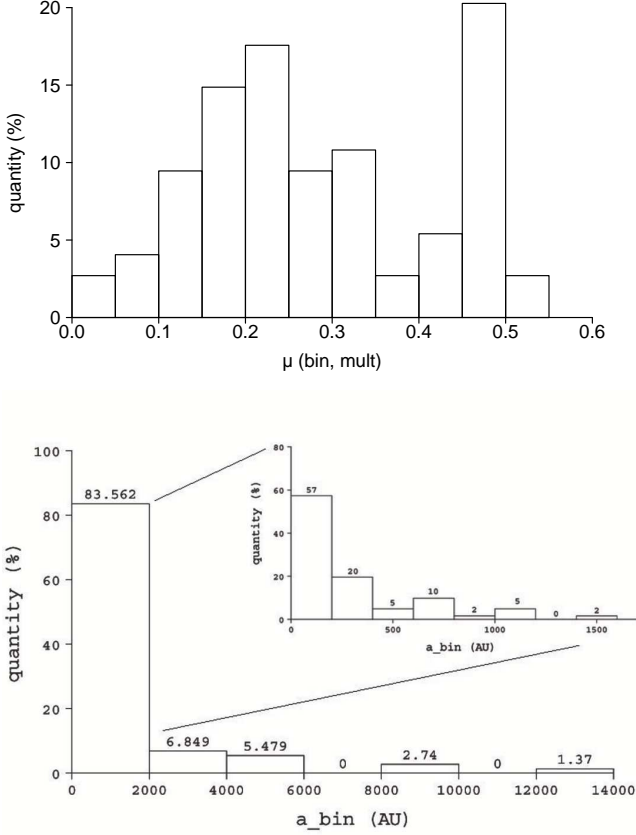


Figure 2. The histogram presents the mass ratio μ_{bin} (upper graph) and the separation (a_{bin} , shown in the lower graph) of all binary star systems with exoplanets (including the binaries in multiple star systems, see Figs. 10, 11), taken from the binary catalogue of exoplanets (<http://www.univie.ac.at/adg/schwarz/multiple.html>). To see the well detached binary systems we zoom into the histogram of a_{bin} in the inset.

of motion. In the S-Type configuration we also investigated close-in planets, therefore we considered the general relativity in our calculations, Beutler (2005).

We considered well detached eclipsing binaries, with distances between the stars of 0.5, 1 and 3 AU. To ensure that the effect of the variations of the mass ratio μ of the binary is included in our study, we considered the following three models:

- **model 1:** $m_1 = m_2 = 1M_{\odot}$, corresponds to $\mu = 0.5$
- **model 2:** $m_1 = 1M_{\odot}$ and $m_2 = 0.5M_{\odot}$, corresponds to $\mu = 0.33$
- **model 3:** $m_1 = 1M_{\odot}$ and $m_2 = 0.1M_{\odot}$, corresponds to $\mu = 0.09$

As shown in Fig. 2 the mass ratio of our models is quite common, when we look at the histogram of the detected exoplanets in binaries and multiple star systems. We changed the other two models ($\mu = 0.33$ and $\mu = 0.09$) because the statistics of other binary catalogues (section 5) are equally-distributed. To get a good estimation about occurring perturbations on the secondary star (to measure ETVs)

we used planets with different masses m_3 : Earth⁴, Neptune⁵, and Jupiter⁶.

2.2 Methods

For the analysis of the orbit we used the method of the maximum eccentricity e_{max} . In former studies we found a good agreement with chaos indicators like the Lyapunov characteristic indicator (LCI) (e.g. Bzszó et al. 2013; Schwarz et al. 2007). The e_{max} method uses as an indication of stability a straightforward check based on the maximum value of the planet's eccentricity reached during the total integration time (T_c). If the planet's orbit becomes parabolic ($e_{max} \geq 1$) the system is considered to be unstable. The e_{max} is defined as follows:

$$e_{max} = \max_{t \leq T_c}(e(t)). \quad (1)$$

2.3 ETVs

Since the first exoplanets in P-Type motion were detected, the investigation of the eclipse timing variation became more and more important. The ETV signal of the secondary star will be induced by an additional planet. This gravitational perturbation affects the motions of the two stars and cause their orbits to deviate from Keplerian. In an eclipsing binary, these deviations result in variations over time and duration of the eclipse.

This method is particularly important in the case when the planet's orbit is not in the line of sight, which causes the absence of a transit signal. However, such planets cause perturbations in the orbit of the transiting star, leading to detectable ETVs. Similar investigations for transit timing variations (TTVs) were done in several articles like e.g. Miralda-Escudé & Adams (2005); Holman & Murray (2005) and Agol & Steffen (2007). The feasibility of the detection of extrasolar planets by the partial occultation on eclipsing binaries was investigated by Schneider & Chevreton (1990). The goal of our work was to show which planet sizes for the S- and P-Type configurations are detectable in the ETV signal of the secondary star with current observational equipment. In order to approximate the detectability of possible extrasolar planets by means of ETVs we used the work of Sybilsky, Konacki & Kozłowski (2010) who investigated the sensitivity of the eclipse timing technique for the ground and space-based photometric observations. They showed in a best-case scenario (excluding e.g. star spots or pulsations), that the typical photometric error (detectable timing amplitude dT) for CoRoT is about dT = 4 sec for a brightness (L) of 12 [mag] and dT = 16 sec for L=15.5 [mag]. Kepler has a dT = 0.5 sec for L=9 [mag] and a dT = 4 sec for L=14.5 [mag]. Future space missions will support the effort to detect smaller planets, like for example:

- PLATO (Planetary Transits and Oscillations of stars) will monitor relatively nearby stars to hunt for Sun-Earth analogue systems (Rauer et al. 2014).

⁴ M_{\oplus} which corresponds to $3 \cdot 10^{-6} M_{\odot}$

⁵ M_{\oplus} which corresponds to $5 \cdot 10^{-5} M_{\odot}$

⁶ M_{\oplus} which corresponds to $1 \cdot 10^{-3} M_{\odot}$

- TESS (Transiting Exoplanet Survey Satellite) space mission is dedicated to detect nearby Earth or super-Earth-size planets on close-in orbits around the brightest M dwarfs (Ricker et al. 2014).

- CHEOPS (Characterising ExOPlanets Satellite) will examine transiting exoplanets of known bright and nearby host stars (Broeg et al. 2013).

For our investigations we will use as detection criterion the photometric precision of CoRoT $dT_{crit} = 16$ sec as well as that of Kepler $dT_{crit} = 4$ sec. We determined the ETVs by calculating the amplitude for the perturbed case, where the planet-induced constant rate of apsidal precession is removed by a linear fit. We also took into account the long-term effects caused by the binaries motion around the systems center of mass and the light travel time effect (Montalto 2010).

3 S-TYPE

Several observations of exoplanets in detached binaries motivated us to investigate the possible detection of exoplanets with ETV's. Therefore we used the configuration "primary star-planet-secondary star" with the following initial conditions:

- **Masses:** As shown in section 2.1 we used different masses for the primary and the secondary star (model 1, 2 and 3), which we think represents a quite common mass ratio for binaries and might be useful for future observations of different stars (see discussion section 5).

For the planets we used three different masses: Jupiter (M_J), Neptune (M_N) and Earth (M_\oplus).

- **Semi-major axis:** We considered eclipsing binaries, with separations between the stars of $a_{bin}=0.5, 1$ and 3 AU. The outermost stability border for the possible exoplanets were taken from the literature (Pilat-Lohinger & Dvorak 2002) and verified by numerical integrations. Within the stability borders we integrated 80 equally distributed configurations in case of $a_{bin}=0.5$ AU and $a_{bin}=1$ AU. For $a_{bin}=3$ AU we used 160 equally distributed configurations.

- **Eccentricity:** The eccentricity of the planet was varied between 0.0 and 0.5 (and divided into 80 data points). The binary's eccentricity was set to 0, 0.2 and 0.4.

- All other orbital elements were set to zero ($\omega = \Omega = M = 0$).

For our computations of the ETV-maps, we changed the distance from the planet to the primary star and the eccentricity of the exoplanet. The grid size of the ETV maps were changed from 80×80 ($a_3 \times e_3$) for a_{bin} 0.1 and 1 AU and extended to 160×80 for $a_{bin}=3$ AU. An example is given in Fig. 3 for model 1 ($M_1 = M_2 = 1 M_\odot$) for 3 different masses of the planets: $1 M_J$ (Fig. 3 upper left graph), $1 M_N$ (upper right graph) and $1 M_\oplus$ (lower graph). The separation of the binaries is $a_{bin} = 1$ AU and they have non eccentric orbits. The stability border for the separation of $a_{bin}=1$ AU for all planets (M_J , M_N and M_\oplus) is roughly $a=0.3$ AU. Close or outside the border, the influence of the secondary becomes too large and the planets escape (see Fig. 3 white region). As one can see the stability border shrinks for higher eccentricities of the planet ($e_3 \geq 0.1$). The timing amplitude dT

of planets with M_J is 10 times larger ($dT : 100 - 1000s$) than for M_N ($dT : 10 - 100s$) and very small for the Earth. For the $dT_{crit} = 4$ sec it is possible to detect Earth-like planets as well as by future space missions, which will have a better time resolution or photometric errors.

Tables 1 and 2 summarise our results. The table for planets with $1 M_J$ is not shown, because for all stable initial conditions the ETV-maps would be 100 percent detectable within the typical photometric error of CoRoT ($dT_{crit} = 16sec$) and Kepler ($dT_{crit} = 4sec$). The Neptune-sized planets are detectable for almost all stable orbits in the ETV-map for $dT_{crit} = 4sec$, whereas for $dT_{crit} = 16sec$ especially the ETVs for small separation of the binaries ($a_{bin}=0.5$) and larger eccentricities ($e_{bin} = 0.2$ and $e_{bin} = 0.4$) are not detectable. This is similar for Earth-like planets. However, much more stable orbits are not detectable for both photometric errors. For $dT_{crit} = 16sec$ almost no ETV signals are detectable (only for $a_{bin} = 3AU$ with the model 2 and model 3 for low values of e_{bin}).

4 P-TYPE

For the investigation of the P-Type systems we used the following initial conditions:

- **Masses:** The masses of the binary stars were chosen according to model 1, 2 and 3 (section 2.1). The planet in P-Type motion was integrated with the mass of Jupiter, Neptune and Earth.

- **Semi-major axis:** For the distances between the two stars we choose 0.5 AU and 1.0 AU. The innermost distance of the planet needed for stable motion was taken from literature (Schwarz et al. 2011) and verified by numerical integrations. To determine the dependency on the distance we integrated 100 equally distributed configurations up to a distance of 5 AU (for a distance between the stars of 0.5 AU) respectively 10 AU (for a distance between the stars of 1.0 AU) from the center of mass of the system.

- **Eccentricity:** The eccentricity of the planet was varied between 0.0 and 0.5. The binary's eccentricity was set to 0, 0.2 and 0.4.

- All other orbital elements were set to zero ($\omega = \Omega = M = 0$).

As an example figure 4 shows the results for model 1, a distance between the stars of 1 AU, a binary eccentricity of 0.0 and a Jupiter-sized planet (left graph) and Neptune-sized planet (right graph). On the x-axes the distance of the planet and on the y-axes its eccentricity is given and the axes are subdivided in a grid of 100×100 initial conditions. The colour code corresponds to the ETVs in minutes, where the white region in the upper left corner corresponds to unstable motion of the planet.

As one can see Jupiter's ETVs range from approximately 10 to 1000 seconds, which is much larger than the limits of observability. However, Neptunes ETVs range from 0.5 to 100 seconds. Thus we can conclude that Jupiter sized planets could be easily detected in such systems, while Neptune sized planets show less strong ETV signals.

To give an overview of the results for the different models and initial conditions we summarise in the following two

Table 1. Percent of detectable ETVs for a Neptune-sized planet in S-Type motion.

a_{Bin} [AU]	e_{Bin}	m_2 [M_\odot]	% of detectable ETVs [16s]	% of detectable ETVs [4s]
0.5	0.01	1.0	15.04	99.90
0.5	0.20	1.0	0.00	99.80
0.5	0.40	1.0	0.00	95.58
0.5	0.01	0.5	53.67	99.95
0.5	0.20	0.5	8.52	99.92
0.5	0.40	0.5	0.00	99.31
0.5	0.01	0.1	81.84	96.41
0.5	0.20	0.1	59.44	99.92
0.5	0.40	0.1	29.03	99.63
1.0	0.01	1.0	67.78	99.86
1.0	0.20	1.0	50.48	99.62
1.0	0.40	1.0	6.06	99.16
1.0	0.01	0.5	80.96	99.53
1.0	0.20	0.5	66.65	99.49
1.0	0.40	0.5	33.59	99.15
1.0	0.01	0.1	85.35	96.08
1.0	0.20	0.1	76.64	99.63
1.0	0.40	0.1	52.47	97.38
3.0	0.01	1.0	90.04	98.87
3.0	0.20	1.0	87.08	98.91
3.0	0.40	1.0	78.99	98.51
3.0	0.01	0.5	94.61	99.09
3.0	0.20	0.5	90.46	98.36
3.0	0.40	0.5	83.53	98.34
3.0	0.01	0.1	96.49	98.68
3.0	0.20	0.1	94.24	97.49
3.0	0.40	0.1	88.44	97.39

Table 2. Percent of detectable ETVs for a Earth-sized planet in S-Type motion.

a_{Bin} [AU]	e_{Bin}	m_2 [M_\odot]	% of detectable ETVs [16s]	% of detectable ETVs [4s]
0.5	0.01	1.0	0.00	0.00
0.5	0.20	1.0	0.00	0.00
0.5	0.40	1.0	0.00	0.00
0.5	0.01	0.5	0.00	0.00
0.5	0.20	0.5	0.00	0.00
0.5	0.40	0.5	0.00	0.00
0.5	0.01	0.1	0.00	56.00
0.5	0.20	0.1	0.00	14.18
0.5	0.40	0.1	0.00	0.81
1.0	0.01	1.0	0.00	18.27
1.0	0.20	1.0	0.00	0.00
1.0	0.40	1.0	0.00	0.00
1.0	0.01	0.5	0.00	52.15
1.0	0.20	0.5	0.00	14.00
1.0	0.40	0.5	0.00	0.00
1.0	0.01	0.1	9.95	68.44
1.0	0.20	0.1	0.00	46.50
1.0	0.40	0.1	0.00	19.36
3.0	0.01	1.0	0.00	73.32
3.0	0.20	1.0	0.00	63.87
3.0	0.40	1.0	0.00	39.17
3.0	0.01	0.5	18.82	85.84
3.0	0.20	0.5	0.00	72.96
3.0	0.40	0.5	0.00	53.29
3.0	0.01	0.1	37.30	89.08
3.0	0.20	0.1	7.45	82.18
3.0	0.40	0.1	0.28	66.44

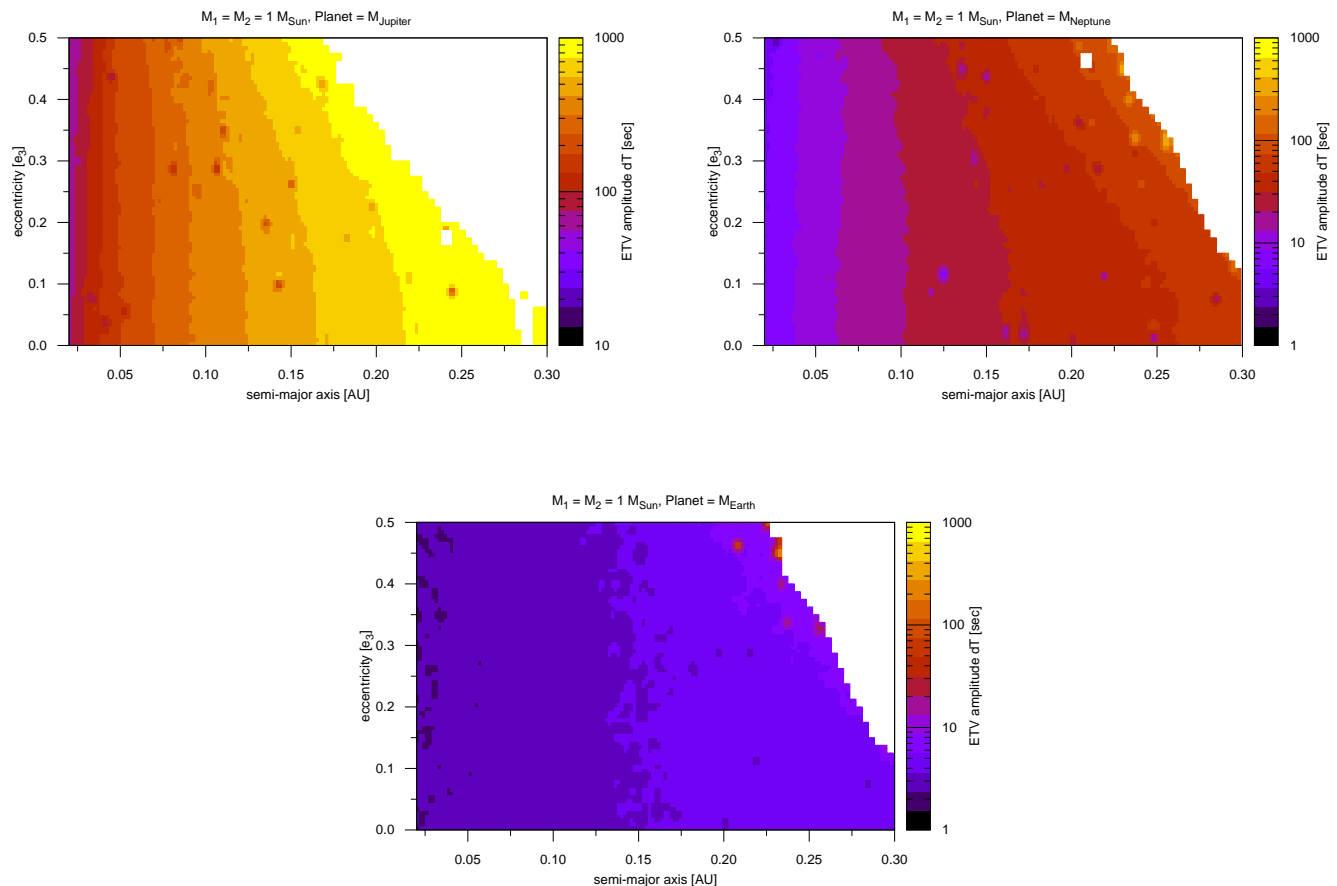


Figure 3. Three different ETV maps in the planar ($i = 0^\circ$) three-body problem for possible exoplanets in S-Type motion for model 1 ($m_1 = m_2 = 1M_\odot$). For the separation between the two stars we choose $a_{bin}=1$ AU with a mass of the planet of $1 M_J$ (upper left graph), $1 M_N$ (upper right graph) and $1 M_E$ (lower graph). On the x-axes the distance of the planet to the primary star is given and on the y-axes its eccentricity. The colour code presents the values of the amplitude of the ETV signal dT in [sec]. The yellow and red regions depicts large values of dT whereas the violet and black regions represent small ones, whereas the white region corresponds to unstable motion of the planet. A colour version of this figure is available in the online version.

tables (table 3 and 4) the percentage of detectable ETV Signals for Jupiter- and Neptune-sized planets. Since different telescopes can reach different resolutions we give the percentage of all orbits, which show ETV signals larger than 4 s and larger than 16 s (last two columns in tables 3 and 4). In the first three columns we give the semi-major axis, the eccentricity and the mass of the secondary.

For Jupiter-sized planets (table 3) all initial conditions produce ETV signals larger than 4 s and nearly all initial conditions produce even ETV signals larger than 16 s. For Neptune-sized planets (table 4) the situation is not that clear, but still nearly all initial conditions produce a quite large amount of ETV signals above 4 s, while the amount of ETV signals above 16 s shrink clearly for lower mass planets. The investigation of Earth-sized planets showed almost no detectable ETV signals. We could find just a few initial conditions (for $a_{Bin} = 1$ AU, $e_{Bin} = 0.2$ or 0.4 and $m_2 = 0.1M_*$) for which ETV signals above 4 s could be found and none for ETV signals above 16 s. From our results we can conclude that circumbinary planets

down to Neptune-size can be detected by using ETVs, while even lower massed planets (i.e. Earth-sized) currently can not be found by ETV signals.

5 STATISTICS ON BINARY STAR SYSTEMS

The space missions CoRoT and Kepler discovered a huge number of eclipse binaries (Maceroni et al. 2011). The eclipsing binary frequency of the first CoRoT fields is 1,2% of all targets. A similar, slightly larger, value of 1.4% is found by Slawson et al. (2011) and Prsa et al. (2011) for the Kepler targets. Most of these binaries have very small periods ($< 10d$), which are not interesting for the S-Type configurations. However, beside these space missions there is a lot of unused data available from former studies, collected in several catalogues. Our survey includes also spectroscopic binaries to find candidates for our numerical investigations and for the catalogue of exoplanets in binary star systems.

Collecting data and information of binary star systems has by now a long history and a considerable amount of cat-

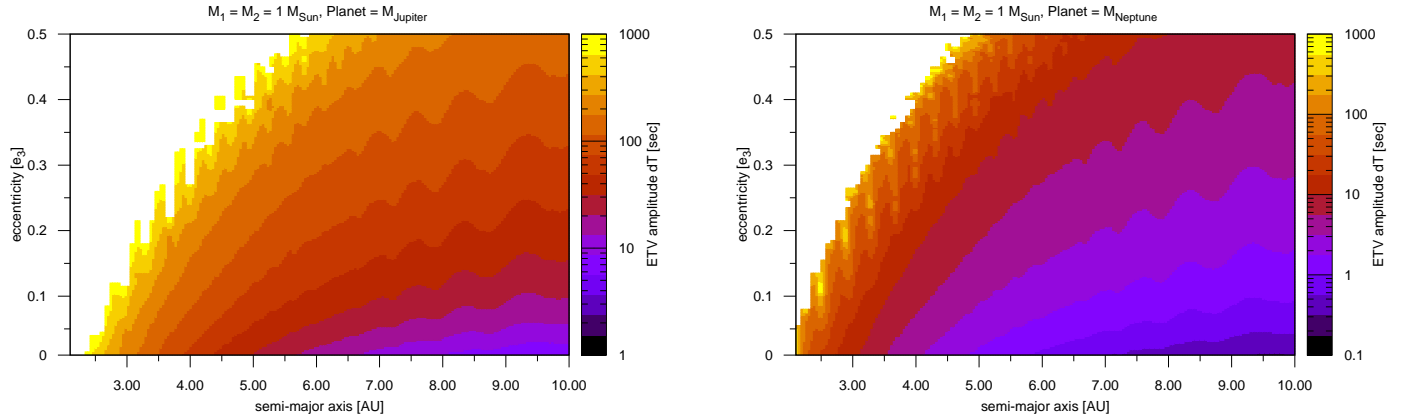


Figure 4. Two different ETV-maps for P-type model 1, a distance between the stars of $a_{bin} = 1AU$, the binaries eccentricity of $e_{bin} = 0$ and a Jupiter-massed planet (left graph) and a Neptune-sized planet (right graph). On the x-axes the distance of the planet and on the y-axes its eccentricity is given. Resulting in a grid of 100×100 initial conditions. The colour code corresponds to dT in sec. A colour version of this figure is available in the online version.

Table 3. Percent of detectable ETVs for a Jupiter-sized planet in P-Type motion.

a_{Bin} [AU]	e_{Bin}	M2 [M_{\odot}]	% of detectable ETVs [16s]	% of detectable ETVs [4s]
0.5	0.01	1.0	73.44	100
0.5	0.20	1.0	100.00	100
0.5	0.40	1.0	100.00	100
0.5	0.01	0.5	80.29	100
0.5	0.20	0.5	100.00	100
0.5	0.40	0.5	100.00	100
0.5	0.01	0.1	83.95	100
0.5	0.20	0.1	100.00	100
0.5	0.40	0.1	100.00	100
1.0	0.01	1.0	92.00	100
1.0	0.20	1.0	100.00	100
1.0	0.40	1.0	100.00	100
1.0	0.01	0.5	93.14	100
1.0	0.20	0.5	100.00	100
1.0	0.40	0.5	100.00	100
1.0	0.01	0.1	98.31	100
1.0	0.20	0.1	100.00	100
1.0	0.40	0.1	100.00	100

alogues has been published in this context. These databases have meanwhile reached a size and complexity, which require not only the consolidation of the existing data but also renewed evaluations and statistical analyses.

One of our main challenges is to collect and aggregate the existing data of the semi-major axes (a), the mass ratios (μ), and the eccentricities (e) given in former catalogues of binary star systems. In this process, we concentrate on previous investigations which include publications since the 1980s as listed in Tab. 5.

An early example of a comprehensive data collection on binary star systems includes the work of Worley & Heintz (1983) which is based on the “Finsen-Worley Catalogue” published in 1970. The “4th Catalogue of Orbits of Visual Binaries” contains orbital elements of about 930 objects in

847 systems, whereby triples are counted as two systems. The statistical distribution of the semi-major axis illustrates that almost 96% of the visual binaries are located at a angular separation of less than 5 arcsec.

In 1988 and 1989, the “15th Complementary Catalogue of SBs” was published by Pedoussaut et al. and Malkov, respectively. This database contains the orbital data and the derived masses of 436 spectroscopic binaries. The statistical analysis of the available data of 310 semi-major axes shows that just above 92% of the stars have an $a \cdot \sin(i) < 200$ AU (minimum distance).

The “Catalogue of eclipsing binaries parameters” of Perevozskina et al. (1999) and Perevozskina & Svechnikov (2004) respectively, not only includes orbital parameters, masses, and luminosities but also photometric orbit data

Table 4. Percent of detectable ETVs for a Neptune-sized planet in P-Type motion.

a_{Bin} [AU]	e_{Bin}	M2 [M_{\odot}]	% of detectable ETVs [16s]	% of detectable ETVs [4s]
0.5	0.01	1.0	0.00	0.00
0.5	0.20	1.0	0.00	40.59
0.5	0.40	1.0	0.00	71.92
0.5	0.01	0.5	0.00	21.03
0.5	0.20	0.5	2.24	63.67
0.5	0.40	0.5	7.79	90.44
0.5	0.01	0.1	0.87	31.56
0.5	0.20	0.1	15.00	86.43
0.5	0.40	0.1	31.95	100.00
1.0	0.01	1.0	0.00	47.49
1.0	0.20	1.0	22.36	95.54
1.0	0.40	1.0	50.92	100.00
1.0	0.01	0.5	1.30	59.51
1.0	0.20	0.5	45.35	100.00
1.0	0.40	0.5	75.19	100.00
1.0	0.01	0.1	13.65	70.58
1.0	0.20	0.1	72.02	100.00
1.0	0.40	0.1	94.87	100.00

Table 5. List of reviewed publications. 'No.' stands for the total number of stars as offered in the according catalogue. '-' implies that no relevant data is available. (*) In these cases, the semi-major axis of the orbit is given in arcsec. Due to the lack of data, they could not be converted into AU.

Catalogues	No.	a (total)	$a < 100$ AU	$a < 20$ AU	$a < 3$ AU	μ or m	e
Worley & Heintz (1983)	933	932(*)	-	-	-	933	-
Budding (1984)	414	-	-	-	-	394	-
Corbally (1984)	170	-	-	-	-	-	-
Pedoussaut et al. (1985)	1207	-	-	-	-	-	-
Pedoussaut et al. (1988)	436	310	254	170	75	253	421
Malkov (1993)	288	-	-	-	-	287	-
Perevozkina et al. (1999)	44	44	44	44	44	-	-
Svechnikov et al. (1999)	113	113	113	113	111	-	-
Liu et al. (2001)	280	-	-	-	-	-	-
Downes et al. (2001)	1314	-	-	-	-	-	-
Mason et al. (2001)	132120	78508(*)	-	-	-	-	-
Udalski et al. (2002)	177	-	-	-	-	-	-
Pribulla et al. (2003)	361	-	-	-	-	116	-
Surkova and Svechnikov (2004)	232	323	232	232	230	-	-
Pourbaix et al. (2004)	4031	-	-	-	-	-	4031
Mermilliod et al. (2007)	157	155	96	24	2	-	157
Ritter and Kolb (2003); Ritter H. (2011)	2072	-	-	-	-	281	-
Mace (2014)	1565	-	-	-	-	-	-
Nicholson (2015)	9450	-	-	-	-	-	-

of 44 eclipsing binary systems whereby all values of a are smaller than 0.5 AU.

Svechnikov et al. (1999) and Svechnikov & Perevozkina (2004) respectively, published the "Catalogue of DMS-type eclipsing binaries" which contains information of 113 binaries with photometric and spectroscopic parameters. The semi-major axis of the detached main-sequence-type eclipsing binaries is illustrated in Fig. 5.

The catalogue of "Semi-detached eclipsing binaries" of Surkova and Svechnikov from the year 2004 is a collection of slightly more than 230 semi-detached eclipsing binary star systems with known photometrical orbital elements. The distribution of the semi-major axes illustrates a significant

accumulation of systems with an a smaller than 0.1 AU. Just over 85% of the eclipsing binaries are located in that area.

The semi-major axis of 155 spectroscopic binaries with red-giant primaries in open clusters (Mermilliod et al. 2007) are shown in the left-hand panel of Fig. 7. Orbital periods range from 2.07 to 689 days (1.89 years). It is apparent from this distribution that almost 62% of the spectroscopic binaries have a semi-major axis smaller than 100 AU with a nearly exponential increase of binaries towards smaller a . The statistical evaluation for $a < 20$ AU is presented in the right-hand panel of Fig. 7. We found out that most of the detected exoplanets in binary-star systems are stars with masses like our sun or slightly smaller (as shown in the cat-

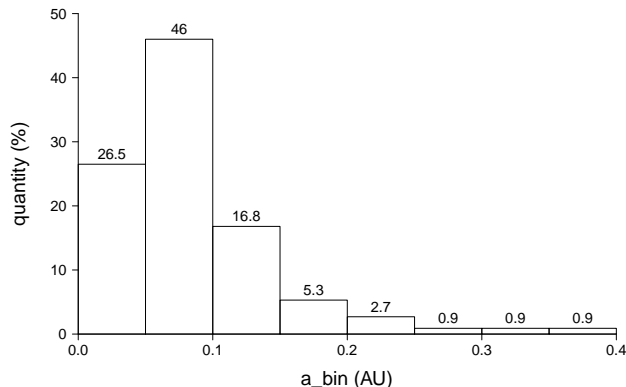


Figure 5. Semi-major axis of 113 DMS-type eclipsing binaries (Svechnikov et al. 1999)

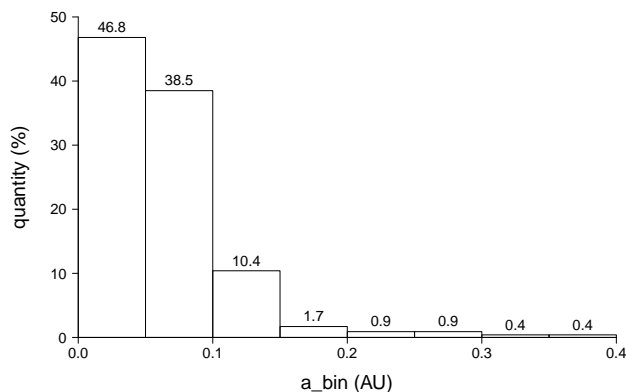


Figure 6. Semi-major axis of 231 eclipsing binaries Surkova and Svechnikov (2004)

alogue of exoplanets in binary star systems). But, Marsh (2011) showed that close pairs of white dwarfs are very common in our Galaxy, with the order of 100-300 million.

It is of particular interest for our study to find binaries within a separation of $a < 3$ AU. Based on our statistics, we have found a set of 462 candidates that fit our requirements. With regard to the planning of possible future catalogues, a uniform classification of the semi-major axis (e.g. in AU) would be preferable in order to evaluate statistical analyses and to provide useful information.

6 CATALOGUE OF EXOPLANETS IN BINARY STAR SYSTEMS

6.1 Motivation for creating the catalogue

The Extrasolar Planets catalogue was the first online catalogue and is available since February 1995 at <http://exoplanet.eu> (Martinache & Schneider 2004). The catalogue has been upgraded in 2005 by additional graphical and statistical online services (Le Sidaner et al. 2007). Other databases followed some years later: the California and Carnegie Planet Search table at <http://exoplanet.org>

(Butler et al. 2006) and the Geneva Extrasolar Planet Search Programmes table (Mayor, Queloz, Udry and Naef) providing first hand data from the observers using the radial velocity and transit method. The advantage of the Extrasolar Planets Encyclopaedia (Schneider et al. 2011) – maintained by the exoplanet TEAM – is that it lists all detection methods (astrometry, pulsar timing, microlensing, imaging etc.).

Cataloguing the data of exoplanetary systems becomes more and more important, due to the fact that they conclude the observations and support the theoretical studies.

Since planets in binary star systems were detected they become more important. In 2013 we started to compile a catalogue for binary and multiple star systems because at that time there did not exist a list of exoplanets in binary star systems. Now also the Open Exoplanet Catalogue shows exoplanets in binary and multiple star systems, which is a community driven and decentralised astronomical database and available at <http://www.openexoplanetcatalogue.com/> (Rein 2012). At the beginning of our catalogue we wanted to supplement the “Extrasolar Planets Encyclopedia”, in agreement and with the support of J. Schneider and his team. In case of binary and multiple star systems the challenge is big due to the fact that the observations are more complicated and the data have much more errors than for single star systems. What concerns us primarily are the statistics, that is why we do not present the errors in our list. If more details are needed, we made a link to the Extrasolar Planets Encyclopedia (the link is contained in the name of the system). Another purpose of our catalogue is to present review statistics of other binary catalogues, which is a big challenge because the catalogues present only very special stars or regions of our galaxy and are non-uniform.

6.2 Binary star systems

The catalogue is described as it was in the year 2016, organised in 12 columns and will be updated monthly. We distinguish detection from discovery, because some planets for example are discovered by radial velocity and detected by transit afterwards.

One can sort in two directions: ascending, meaning from the lowest value to the highest, or descending. For example, by clicking on the header e.g. discovery the list will be sorted after the largest value, when you click again it will be sorted after the smallest value. The list is originally sorted by the distance between the binaries (a_{bin}), all rows can be sorted in the same way except the comments. In addition an introduction and help is also given in the menu bar of the catalogue including an example list. To make your own statistics the data is available as .csv file. All systems are linked to The Extrasolar Planets Encyclopedia some of the systems to the Open Exoplanet Catalogue where one can find references and additional data on the systems.

6.2.1 Star Data

This part of the catalogue represents only the stellar data of the system (see Fig. 8).

System

Name or designation of the system and the structure of

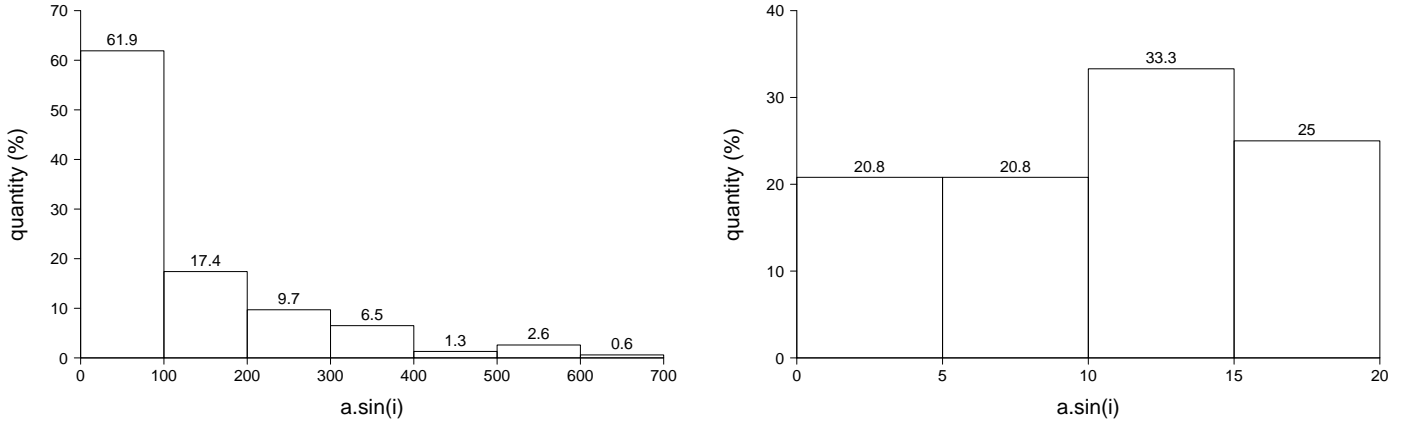


Figure 7. Left-hand panel: Semi-major axis of 155 spectroscopic binaries (Mermilliod et al. 2007). Right-hand panel: Semi-major axis of 24 spectroscopic binaries with $a < 20$ AU (Mermilliod et al. 2007).

the system, where capital letters refer to a star, and small letters refer to a planet. Example: DP Leo AB b "Ab B" or "A Bb" referred to a S-Type planet, while "AB b" refer to a P-Type planet as marked in the column on the planetary motion.

Discovery

Gives the year of the first discovery.

Spectral type

This shows the spectral types of the stars. Unfortunately the data for some systems is incomplete.

Distance [parsec]

Distance from the Sun to the system in units of parsecs (1 parsec = 3.26 light-years).

Mass ratio (μ)

Given as dimensionless proportion $\mu = \frac{m_2}{(m_1 + m_2)}$, where m_1 is the mass of the first star and m_2 is the secondary star's mass.

a_{binary} [AU]

Represents the distance between the double stars given in astronomical units. If the semi-major is not given, a minimum of a_{binary} will be approximated trigonometrically by the published separation angle α given in [arcsec] and the distance from the Sun to system d given in [parsec].

$$a = d \cdot \tan \alpha$$

Eccentricity (e_{sec})

Represents the eccentricity of the second star. This parameter is very rarely known.

Number of planets

Systems with one planet are dominant, but multiplanet systems become more and more frequent.

Planet motion S-type, P-type

As shown in the introduction see also Fig. 1.

Mass: m_1 [M_\odot] and m_2 [M_\odot]

Mass of the first and the second star given in units of the masses of our Sun.

Mass $M \times \sin i$

The portion of a distant planet's mass that is detectable is determined by its line of sight, when observed from Earth. If the angle of inclination from the "face-on" position is "i", then the component which is in line with the Earth is given by $\sin(i)$.

Semi-major axis [AU]

Represents the semi-major axis of the planet's orbit given in astronomical units. If the semi-major is not given, it will be derived from the published orbital period and from the mass of the host star through the Kepler law.

$$a = \sqrt[3]{\frac{G \cdot M_* \cdot P^2}{4 \cdot \pi^2}}$$

For S-type: M_* is the mass m_1 of star 1 or m_2 of star 2 depending on the planet's orbit. For P-type: M_* is the sum of the masses m_1 and m_2 . These approximations are strongly influenced by the star's masses.

Orbital period [d].

Represents the orbital period of the planet given in days.

Eccentricity

Represents the eccentricity of the planet.

Argument of perihelion [deg]

Represents the angle from the body's ascending node to its periapsis, measured in the direction of motion.

Radius [R_J]

Represents the planet's radius given in units of one Jupiter radius.

Inclination

This value does not always represent the orbital inclination of the planet, especially for transiting planets it shows only the inclination relative to the line of sight.

Detection method

Shows the different detection methods which were used for the observations.

6.2.2 Planet Data

Here we present the data of the planets, where the first two columns are similar to the star data (see Fig. 9).

6.3 Multiple star systems

Beside binary star systems also multiple star systems may harbour exoplanets. The different possibilities for triple star

Binary Catalogue of Exoplanets

Exoplanets in binary star systems — Star data

Binary Catalogue Home Star Data Planet Data Download data as CSV file Introduction and Help											
Show 10 entries	Search:										
System [▲]	Discovery	Spectral Type	Distance [parsec]	Mass ratio [m2/(m1+m2)]	a _{binary} [AU]	e _{sec}	Number of planets	Planet motion S-type, P-type	m1 [m _{sun}]	m2 [m _{sun}]	Comments
DP Leo AB b	2009	DA / M5V	400.00	0.015	0.0027	0.00	1	P	0.6	0.009	p=1.4967h
FW Tau AB b	2013	M4 / ?	145.00	0.500	11		1	P	0.12	0.12	
g Cep Ab B	2003	K2V / ?	13.79		20.3	0.36	1	S	1.4		
Showing 1 to 3 of 3 entries											
										Previous	1 Next

Figure 8. Excerpt from the table of discovered systems with the known data for the stars. A colour version of this figure is available in the online version.

Binary Catalogue of Exoplanets

Exoplanets in multiple star systems — Planet data

[Binary Catalogue Home](#) |
 [Star Data](#) |
 [Planet Data](#) |
 [Download data as CSV file](#) |
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Show 10 entries

Search:

System [▲]	Discovery	Mass - M x sin i [M_Jupiter]	Semi-major axis [AU]	Orbital period [d]	Eccentricity	Argument of perihelion [deg]	Radius [R_J]	Inclination	Detection method
Kepler 432 b	2014	5.41	0.310	52.501	0.512	65.60	1.45	88.17	transit / rad. vel.
Kepler-14 b	2011	8.400		6.79012	0.035		1.136	90	transit
Kepler-16 b	2011	0.333	0.7048	228.776	0.007	318.00	0.7538	90.0322	transit

Showing 1 to 3 of 3 entries

Previous

1

Next

Figure 9. Excerpt from the table of discovered systems with the known data for the planets. A colour version of this figure is available in the online version.

systems are shown in Fig.10, whereas quadruple star systems are presented in Fig.11.

6.3.1 Star Data

In this list the first three columns are similar to the list of the binary star systems.

a_{triple} or a_{quadruple} [AU]

Distance in AU of the third star from the inner binary, or of the two binaries from each other.

a_{binary1} [AU]

Separation of the inner binary in case of a triple star system.

a_{binary2} [AU]

Separation of the other binary in case of a quadruple star

system.

Number of planets

Systems with one planet are dominant, but multiplanet systems become more and more frequent.

Number of stars

Total number of detected stars in a multiple star system.

Mass of m₁ - m₄ [M_☉]

Mass of the 1st, 2nd, 3rd and 4th star given in units of the mass of our Sun.

6.3.2 Planet Data

The list is completely identical with the planet data list of binary star systems.

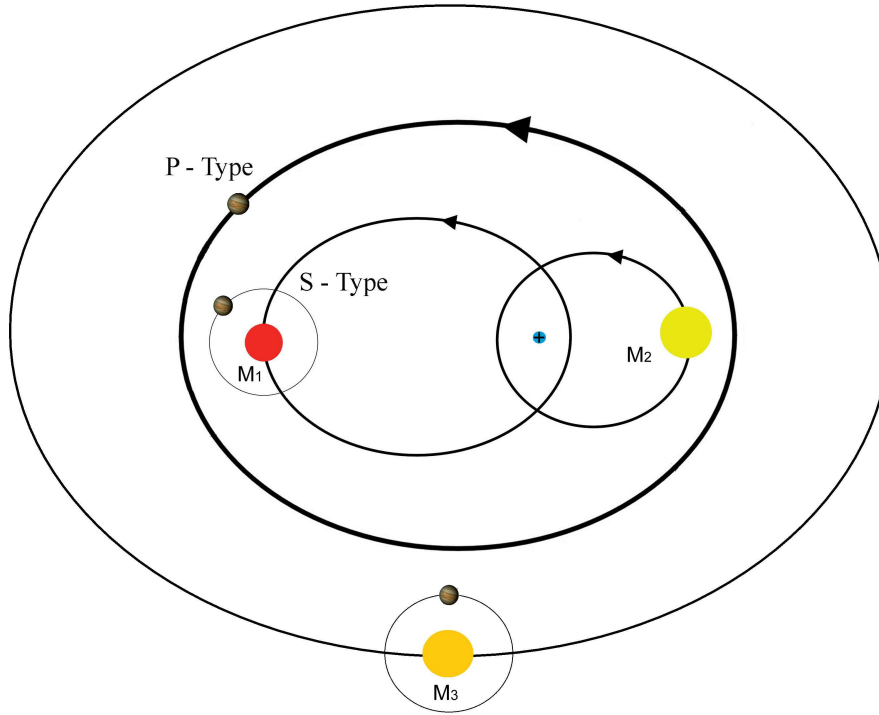


Figure 10. Scheme of the different dynamical possibilities of exoplanets in triple star systems. The symbol "+" marks the center of mass of the system. A colour version of this figure is available in the online version.

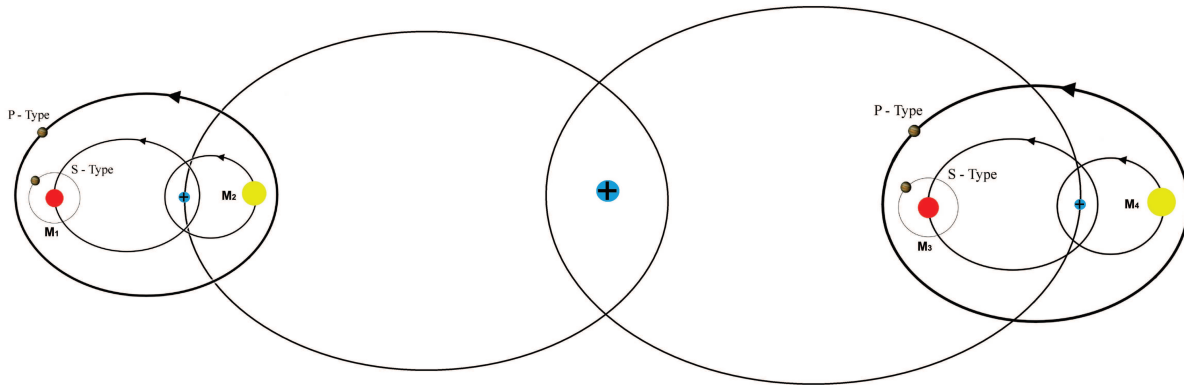


Figure 11. Scheme of the different dynamical possibilities of exoplanets in quadruple star systems. The symbol "+" marks the center of mass of the system. A colour version of this figure is available in the online version.

7 CONCLUSIONS

In this article we used the statistics of the binary catalogue of exoplanets, which we introduce in the appendix. We prepared statistics of exoplanets in well detached binary systems. In the second part of the article we enlarged the statistics by the investigation of well detached binary star systems from several catalogues and discussed the possibility of further candidates. Finally we investigated the possibility to detect exoplanets in well detached binary systems with eclipse timing variations.

In the statistics of the binary catalogue of exoplanets

we could show that the separation which we used for our calculations are not only of theoretical interest (Fig. 2, lower graph). This also applies for the mass ratios which we used in the models 1,2 and 3 (see section 2.1 and Fig. 2, upper graph). We enlarged our investigation with further studies of well detached binary star systems from several catalogues and discussed the possibility of further candidates. These investigations resulted in 462 candidates have star separations not larger than 3 AU. This is the separation which we investigated in the ETV study.

In this paper we studied the circumstances favourable to detect S- and P-Type planets in well detached binary-

star-systems using eclipse timing variations (ETVs). To determine the probability of the detection of such variations with ground based telescopes and space telescopes, we investigated the dynamics of well detached binary star systems with a star separation in the range of $0.5 \leq a_{bin} \leq 3\text{AU}$. We performed numerical simulations by using the full three-body problem as dynamical model. The stability and the ETVs are investigated by computing ETV maps for different masses of the secondary star (model 1-3), separations ($a_{bin} = 0.5, 1$ and 3AU) and eccentricities ($e_2=0, 0.2$ and 0.4). In addition we changed the planet's mass (Earth, Neptune and Jupiter size) eccentricities ($e_3=0-0.5$) and semi-major axis (depending on the configuration S- or P-type). For our investigations we used as detection criterion the photometric precision of CoRoT $dT_{crit} = 16\text{ sec}$ as well as that of Kepler $dT_{crit} = 4\text{ sec}$, which we think is a realistic limit. In general the ETV amplitude dT depends mainly on the eccentricity, the semi-major axis and the mass of the planet. The stars separation and eccentricity (e_2) mainly restricts the stable region of the planets. We conclude that many amplitudes of ETVs are large enough to detect exoplanets – with Neptune and Jupiter-sizes – in S-type and P-type configurations. Whereas for the S-type configuration also Earth-size planets provide detectable ETV signals.

We can conclude that possible terrestrial-like planets are detectable in binary star systems by the help of eclipse timing variations with restrictions. However, future space missions will have a better precision which will enlarge the number of detectable ETV signals.

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